Role of Air-Breathing Pulse Detonation Engines in High Speed Propulsion

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ABSTRACT

In this paper, the effect of flight Mach number on the relative performance of pulse detonation engines and gas turbine engines is investigated. The effect of ram and mechanical compression on combustion inlet temperature and the subsequent sensible heat release is determined. Comparison of specific thrust, fuel consumption and impulse for the two engines show the relative benefits over the Mach number range.

INTRODUCTION

In a previous publication,[1] the impact of dissociation and the resultant sensible heat addition effect on pulse detonation engine (PDE) performance was investigated. Comparisons were carried out with a gas turbine engine using a thermodynamic cycle analysis. The results showed, for the first time in the literature,[1] a decrease in the sensible heat available for the PDE, which generally caused lower performance. In this paper, a more detailed analysis is made of the effect of changing inlet conditions on the sensible heat release in a PDE and a gas turbine, as well as investigating the performance changes associated with high Mach number flight.

ANALYSIS AND PROCEDURE

A stoichiometric propane-air mixture was specified at an initial temperature and pressure. The detonation and deflagration properties were obtained using the method by Pratt,[2] which is based on the *CEA* program of McBride and Gordon.[3] The results yielded the equilibrium properties of the products and the sensible heat release, h_{PR}. A non-dimensional heat release, $\tilde{q}$, was defined and then determined from the relationship:

$$\tilde{q} = f\, h_{PR}/c_p\, T_0$$

where f is the fuel air mass ratio.

The resulting $\tilde{q}$ was used to perform cycle calculations for the PDE and Brayton cycles. The thermodynamic cycle analysis was based on a modified version of the work of Pratt and Heiser.[4] The modification provides for variable specific heat, specific heat ratio and reference temperature. The cycle analysis yields the maximum theoretical performance for an ideal PDE and Brayton cycle. The analogy with the Otto and Diesel cycle analyses is noted. Further, it is noted that the PDE performance is based on a closed form solution for the leading edge normal shock wave Mach number and entropy rise of the detonation wave, and does not rely on a surrogate analysis such as the Humphrey cycle. The relationship of $\tilde{q}$ to the Chapman-Jouget parameters is given by:

$$\tilde{q} = \frac{\psi\left(M_{CJ}^2 - 1\right)^2}{2(\gamma + 1)M_{CJ}^2}$$

where ψ is the temperature ratio T_3/T_0.

The approach used herein is a closed thermodynamic cycle analysis rather than an integration over a cycle of an unsteady solution of the instantaneous pressures

acting on the PDE tube. Further, it is assumed that isentropic compression and expansion occurs with the detonation device. These processes will give the upper limit of the performance potential for a PDE.

RESULTS

Static condition, $V_0=0$
A stoichiometric mixture of propane and air was selected at an initial reference temperature of 400 °R and a pressure at 3.8 psi. These conditions correspond to those at an altitude of 6.2 mi. The heat release was calculated from the equilibrium code.[2] The calculations for the sensible heat release yielded h_{PR} values of 1.6×10^4 (PDE) and 1.8×10^4 BTU/lb$_m$ (Brayton) at a ψ (=T_3/T_0) value of 1. The initial sensible heat addition, figure 1, is about 12 percent lower for the detonation process than for the deflagration. The temperature ratio, ψ, was then varied over the range from 1 to 5. The results are shown in figure 1.

The thermal efficiencies for the two cycles were calculated and are shown in figure 2 and is defined as

$$\text{eff-th} = 1 - \frac{\text{heat rejected}}{\text{heat added}}.$$

It is noted that the PDE efficiency exceeds that of the Brayton over the range of temperature ratios. However, the sensible heat release for the Brayton exceeds that of the PDE as shown in figure 1. These two varying parameters determine the relative performance of the two cycles.

The specific thrust values calculated from the sensible heat release and thermal efficiency values for the Brayton and PDE cycles are shown in figure 3 as a function of ψ. The significant feature of figure 3 is that the PDE specific thrust crosses over the Brayton cycle curve at a temperature ratio of 2.25. This result is due to the lower sensible heat available in the PDE, and to the decreasing value of thermal efficiency for the PDE relative to the Brayton. Since, the specific thrust is given by:

$$\frac{F}{\dot{m}_o} = \frac{1}{g_c}\left[\sqrt{V_0^2 + 2\eta_{th}\tilde{q}c_p T_0} - V_0\right]$$

it may be seen that for $V_0 = 0$, when the products of the thermal efficiency and heat release become equal, the specific thrusts have a common value. As the thermal efficiency difference diminishes between the two cycles, and with a larger Brayton cycle heat release value, the Brayton cycle performance will eventually exceed that of the PDE. As shown in figure 3, the performance advantage for the PDE occurs at a temperature ratio value below 2.25.
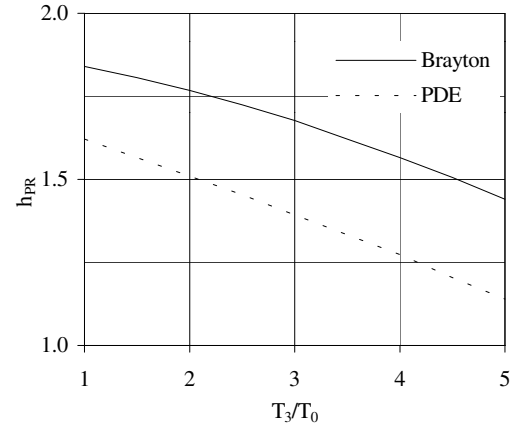

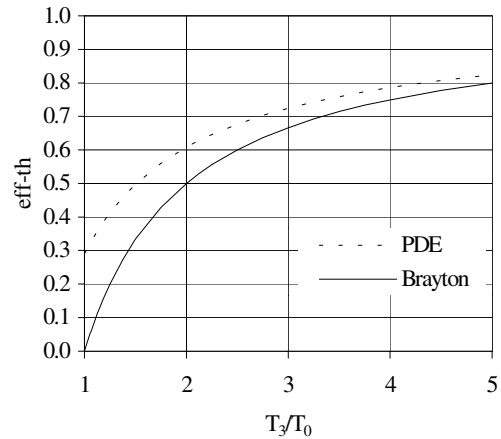Figure 1. Sensible heat release ($\times 10^4$ BTU/lb$_m$) for the Brayton and PDE cycles.

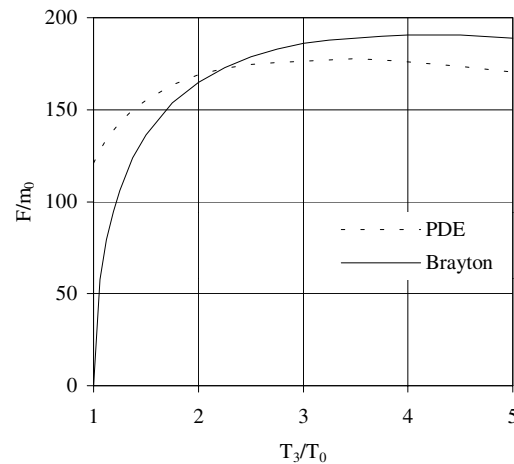Figure 2. Thermal efficiencies for the PDE and Brayton cycles, γ=1.25.

Figure 3. Specific thrust (lb$_f$-s/lb$_m$), γ= 1.25.

<u>Effect of Forward Velocity</u>
The specific thrust calculations were performed for flight Mach numbers from 1 to 4, where 980 ft/s is equal to the speed of sound at the altitude of 6.2 miles and a free-stream gamma value of 1.4. For these calculations it was assumed that the combustor entrance temperature value was equal for both cycles, and the gamma for the combustion was 1.25. The results are shown in figure 4. In all cases, it is seen that the PDE offers only a small potential benefit over the Brayton cycle over the investigated speed range. The PDE benefit exists at ψ values less than 2.25, which is the same value observed for static conditions. This crossover value remains fixed since all of the performance parameters derive from the same thermal efficiency curves.

The relationship between Mach number and temperature ratio is given by the expression

$$M_0 = \sqrt{2(\psi - 1)/\gamma_\infty - 1} \; ,$$

and the Mach number variation for γ_∞=1.4 is shown in figure 5.
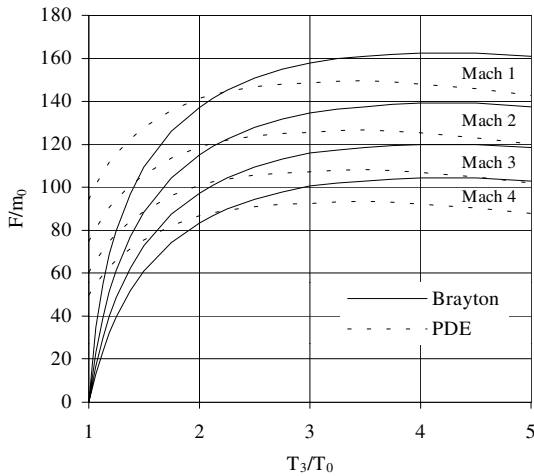

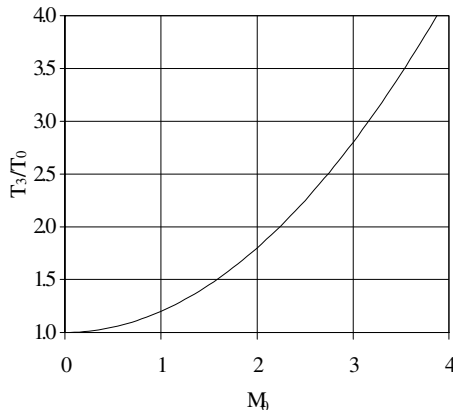Figure 4. Mach number effect on specific thrust.

Figure 5. Mach number effect on minimum temperature ratio.

It may be seen that for a given Mach there exists a value of ψ due to the heating (ram and/or mechanical compression) occurring through the inlet and compressor. For a given Mach number, therefore, a minimum value of ψ exists, below which physically meaningful results are not possible. Using the values from figure 5 allows us to establish physical boundaries for the results shown previously in figure 4. Figure 6 shows the data from figure 4 with these limits imposed, and illustrates the effect they have on narrowing the operating range over which the specific thrust of the PDE is greater than that of the Brayton cycle.
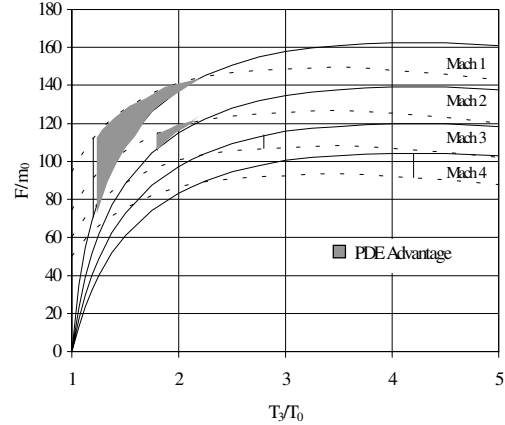

Figure 6. Regions where the PDE cycle performance exceeds that of the Brayton cycle.

It is seen that the PDE offers a specific thrust advantage for a flight Mach number of 1 only above the lower boundary where ψ =1.2. In addition, the upper bound is established by the crossover point with the Brayton cycle, or ψ = 2.25. Hence, only a narrow operating range exists over which the specific thrust for the PDE exceeds that of the Brayton cycle. At Mach 2 the minimum allowable ψ value is 1.8 and the upper boundary remains at 2.25. Therefore, the PDE performance benefit range is reduced to the small range shown in figure 6. At Mach 3, the lower ψ limit increases to 2.8, which is greater than the crossover point between the PDE and Brayton cycles. Therefore, there is no operating range over which the PDE offers a performance advantage at this velocity. At a Mach number of 4, the minimum allowable inlet temperature ratio of 4.2 greatly exceeds the crossover point. As with the Mach 3 condition, no performance benefits accrue with the PDE relative to the gas turbine. As discussed previously,[1] other advantages such as system weight, cost and complexity must exist in order to select a PDE device instead of a gas turbine engine.

The comparisons presented in figures 3, 4, and 6 are based on the assumption that the PDE and Brayton cycles have identical inlet conditions, and therefore

equal T_3 values. In reality, both cycles would have the same ram compression, but the Brayton cycle would have some addition compression due to the presence of a mechanical compressor. The PDE is designed to avoid the complexities of the moving parts associated with mechanical compressors by relying solely on ram compression. This difference in configuration results in different T_3 values at a given flight Mach number. The effect of these different inlet configurations is shown Figure 7. Here, the maximum specific thrust is plotted against flight Mach number. The compression ratio ($\pi_c = P_3/P_2$) for the Brayton cycle is added as an additional parameter for this figure. In addition, a compressor exit temperature of 1250 °F is set as a material limit. The bold lines show the range of operation permissible with this temperature limit and the faint lines are for the case of unlimited temperature.

Increasing the compressor exit temperature limit allows for slightly higher maximum operating speeds for all configurations. This effect is reduced with increases in compressor pressure ratios. The operating ranges for the different configurations with compressor exit temperature limits of 1300 °F and 1450 °F are shown in figures 8 and 9.

The data presented in figure 7 assumes a constant value of π_c for all flight Mach numbers. In reality, the compression ratio is reduced at higher flight velocities to achieve optimum performance. A realistic variation for the compression ratio for the Brayton cycle is shown in figure 8.

Reducing the pressure ratio at higher Mach numbers increases the maximum specific thrust available from the Brayton cycle. The effect of using this pressure ratio schedule and the corresponding ram compression
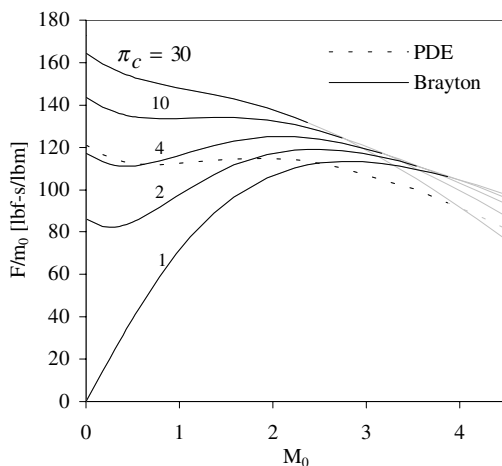
values are shown in figure 11. It is noted that the variation in pressure ratio only has a significant effect on performance at high Mach numbers where the compressor exit temperature limit is exceeded.
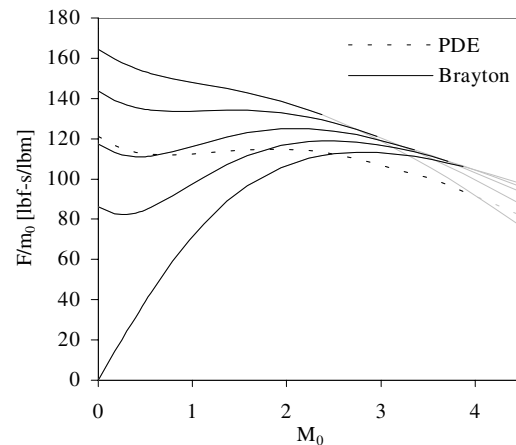

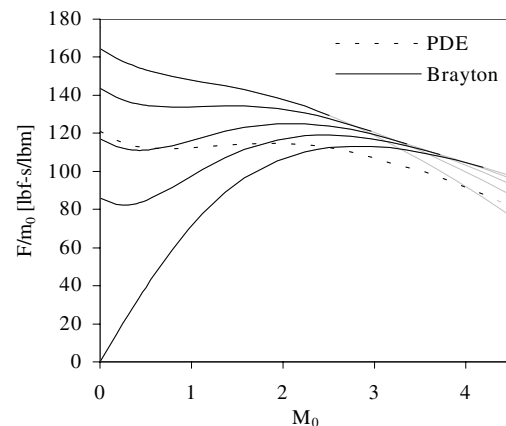Figure 8. Specific thrust for PDE and Brayton cycles, $T_{3\,max} = 1300$ °F, constant values of π_c.

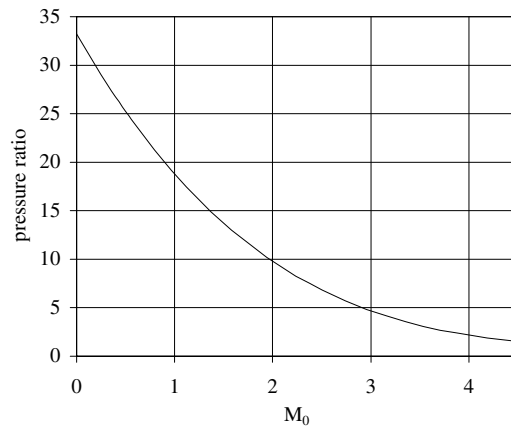Figure 9. Specific thrust for PDE and Brayton cycles, $T_{3\,max} = 1450$ °F, constant values of π_c.

Figure 7. Specific thrust for the PDE and Brayton cycles, $T_{3\,max} = 1250$ °F, constant values of π_c.

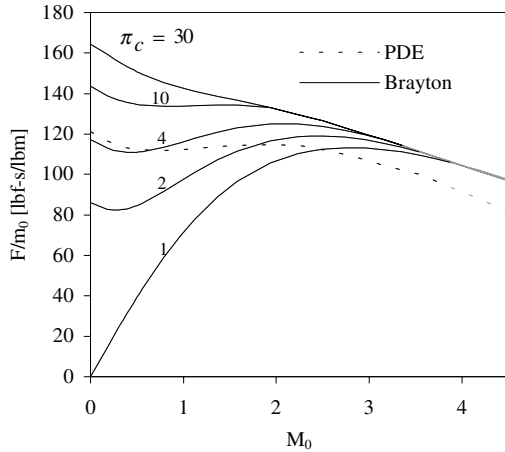Figure 10. Compressor pressure ratio variation for the Brayton cycle.

Figure 11. Specific thrust, variable π_c, T_{3max}=1250 °F.

Figure 12. Specific impulse, variable π_c, T_{3max} = 1250 °F.

Clearly, the PDE cycle enjoys a performance benefit as long as the Brayton cycle is operating at unrealistically low compression ratios. It quickly loses that benefit as the Brayton compressor pressure ratio exceeds a value of 4. The PDE can only match the Brayton cycle if higher PDE compression ratios can be obtained; suggesting a combined cycle configuration which would not be a pure PDE such as a PDE and dual-mode ramjet.

The specific impulse = $f/(F/m_0)$ and the fuel consumption are shown in figures 12 and 13 for the corresponding variables of figure 11.

Figure 13. Specific fuel consumption, variable π_c, T_{3max} = 1250 °F.

The performance calculations so far have been based on ideal process efficiencies. Reference 4 developed the relationships for non-ideal processes and that approach is used herein. Figures 14 to 16 show the effect of reduced expansion efficiencies on the relative performance of the PDE and Brayton cycles. In all these figures, the expansion efficiency is reduced to 0.95 while maintaining ideal compressor and burner efficiencies. The ideal process efficiency curves are shown in the background for reference. These results indicate that the performance of both configurations is reduced for all Mach numbers, but the PDE cycle performance decreases more than the Brayton cycle. This can be seen by comparing the crossover point between the PDE curve and the Brayton curve for π_c=4. For the ideal process efficiencies, the PDE exhibits a slight performance advantage until a Mach number of 0.6. With η_e=0.95, the PDE curve remains below the Brayton curve for all Mach numbers.
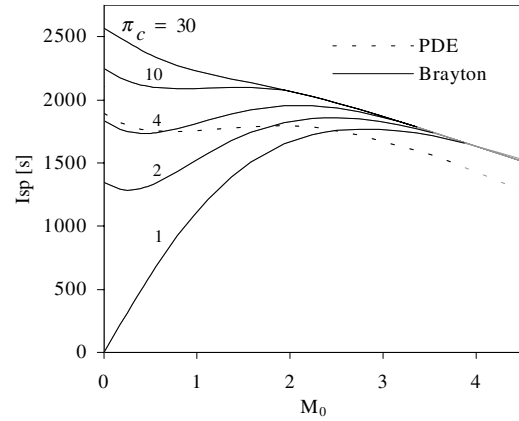

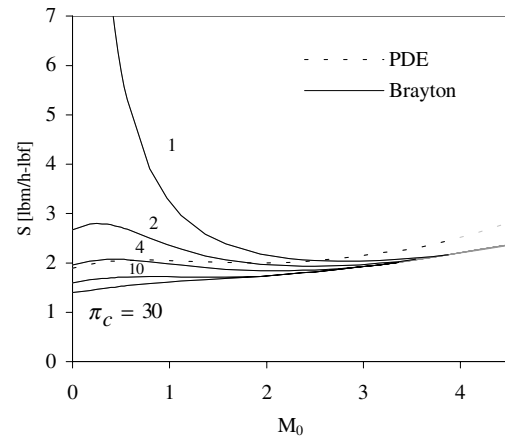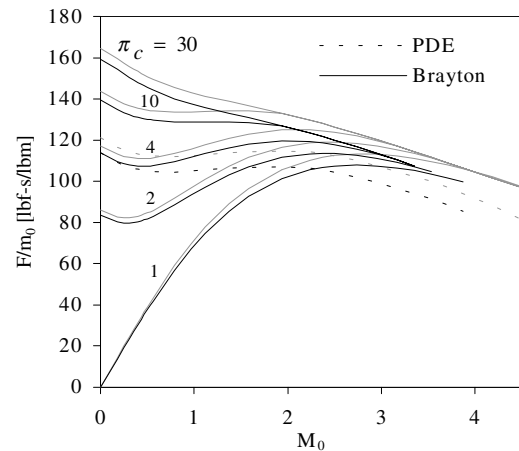Figure 14. Specific thrust, variable π_c, T_{3max}= 1250 °F, η_c=1.0, η_b=1.0, η_e=0.95.
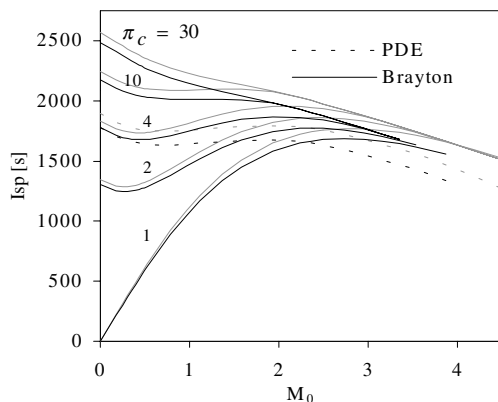
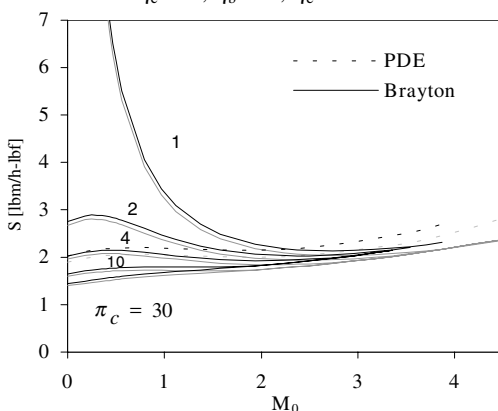Figure 15. Specific impulse, variable π_c, T_{3max} = 1250 °F, η_c=1.0, η_b=1.0, η_e=0.95.

Figure 16. Specific fuel consumption, variable π_c, T_{3max} = 1250 °F, η_c=1.0, η_b=1.0, η_e=0.95.

Figure 17. Specific thrust, constant π_c, η_c=0.95, η_b=1.0, η_e=1.0.

Figure 18. Specific thrust, constant π_c, η_c=0.95, η_b=1.0, η_e=0.95.

Figure 19. Specific thrust, variable π_c, T_{3max} = 1250 °F, η_c=1.0, η_b=0.95, η_e=1.0.

Figure 17 shows the effect of reduced compressor efficiencies on engine performance. It is apparent that a reduction in compressor efficiency has the opposite effect of the reduction in expansion efficiency by slightly improving the relative performance of the PDE. If the compressor and expansion efficiencies are both lowered, the relative performance between the PDE and Brayton cycles remains fairly constant. This is illustrated in figure 18, where the compressor and expansion efficiencies are both set at 0.95.

A reduction in burner efficiency, shown in figure 19, has an even greater effect on reducing the performance of the PDE relative to the Brayton cycle.

Reducing the nozzle efficiency further, to 0.90, for the same parameters as in figure 14 shows a significant drop in the performance. The results are seen in figure 20, and underscore the importance of nozzle performance to the PDE and Brayton cycles.
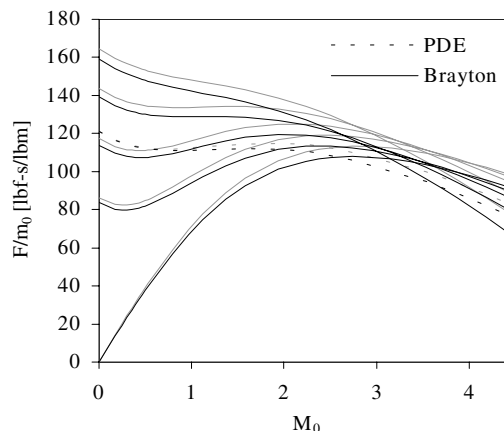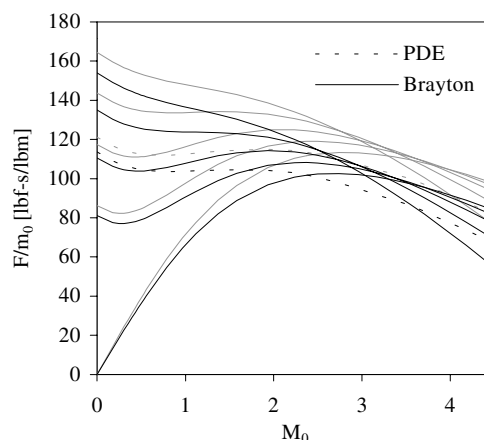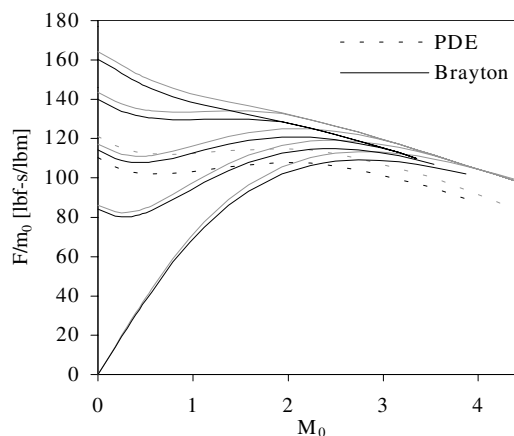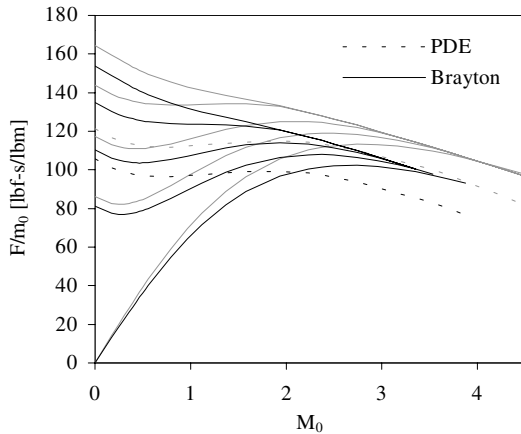
Figure 20. Specific thrust, variable π_c, T_{3max} = 1250 °F, η_c=1.0, η_b=1.0, η_e=0.90.

Figures 21 to 23 show the effect of reduced compressor, burner and expansion efficiencies on the increase in overall thermal efficiency of the two cycles. Figure 21 shows the effect of reduced compression efficiency. The only difference between the two sets of curves is that the background set has η_c=1.00 whereas the foreground set has η_c=0.95. The five percent reduction in compression efficiency has almost no impact on the point where the PDE and Brayton curves cross, indicating that it has very little impact on the relative performance of the two cycles.

Figure 22 examines the effect of the burner efficiency. Here the background curves were calculated with η_b=1.00 and the foreground curves with η_b=0.95. The reduced burner efficiency causes the crossover point of the PDE and Brayton curves to move from a temperature ratio around ψ=3 to ψ=2.5. This means that a reduction in burner efficiency has a significant impact on the relative performance of the PDE and Brayton cycles.

Figure 23 shows the effect of expansion efficiency on the overall thermal efficiency. The five percent reduction in expansion efficiency causes the intersection point of the PDE and Brayton curves to be reduced by more than 1. This shows that the relative performance of the two cycles is most sensitive to the expansion efficiency.
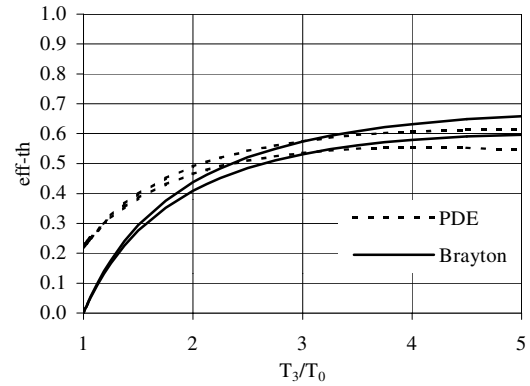

Figure 21. Thermal efficiency, η_c=0.95, η_b=1.00, η_e=0.90. Background: η_c=1.00, η_b=1.00, η_e=0.90.
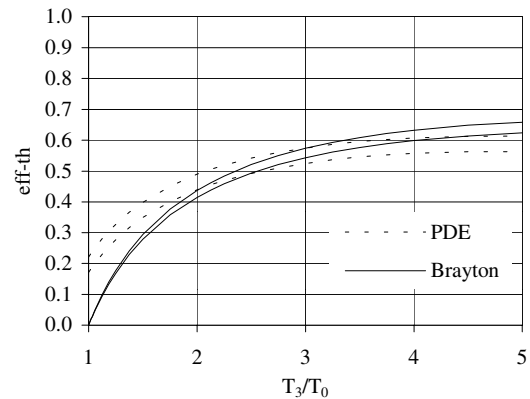

Figure 22. Thermal efficiency, η_c=1.00, η_b=0.95, η_e=0.90. Background: η_c=1.00, η_b=1.00, η_e=0.90.
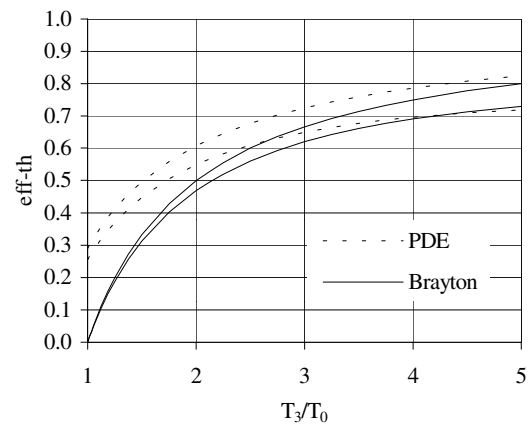

Figure 23. Thermal efficiency, η_c=1.00, η_b=1.00, η_e=0.95. Background: η_c=1.00, η_b=1.00, η_e=1.00.

CONCLUSIONS

Performance parameters for a pulse detonation engine were compared with that of a gas turbine engine. The PDE exhibited a significant static (no forward velocity) performance benefit when compared with the gas turbine engine whose compression ratios were lower than 4. However, that benefit quickly disappeared as the Brayton compressor pressure ratio exceeded a value of 4.

The sensible heat release for both the detonation and the deflagration processes were determined over a Mach number range from 0 to 5 using an equilibrium calculation. As shown previously,[1] there is a 12% reduction in the sensible heat release for the detonation process in the PDE compared to the deflagration process in the Brayton cycle. This reduction is due to the larger degree of dissociation in the PDE. The effect of dissociation on sensible heat release is a primary cause for reducing the specific thrust of a pulse detonation engine relative to a gas turbine engine.

Calculations were performed to examine the effect of Mach number on the performance of the PDE and gas turbine engines. The PDE was found to have higher specific thrust at subsonic Mach numbers relative to the gas turbine engine whose compression ratios were lower than 4. This trend is reversed as the gas turbine compression ratios become higher than 4.

As the flight Mach number increases to sonic and higher, the PDE performance decreases. At sonic speeds, the PDE and Brayton with pressure ratio of 4 are equal. At a Mach number of 2, the PDE and Brayton with a pressure ratio of 2 are equal and at Mach 3, the PDE is lower than the Brayton with no mechanical compression (i.e., only ram compression or a ramjet). For reasonable Brayton compression ratios (10 to 30) the PDE performance was always lower, having lower specific thrust, lower impulse and higher specific fuel consumption.

The performance calculations were also examined for non-ideal process efficiencies, i.e., compression, burning and expansion. For the ideal nozzle expansion, the PDE had a slight performance advantage up to a Mach number of 0.6 compared to a Brayton compression ratio of 4. With a 0.95 nozzle efficiency, the PDE performance remains below the Brayton for all Mach numbers.

A reduction in compressor efficiency was found to slightly improve the relative performance of the PDE, and for a reduction in both the compressor and expansion efficiencies, the relative performance between the two cycles remained fairly constant.

A reduction in burner efficiency had a larger effect on reducing the PDE relative to the Brayton cycle. Further reducing the nozzle efficiency to 0.90 caused a large reduction in PDE performance as shown previously.[4] Inspection of these trends using the thermal efficiency curves also shows that the relative performance of the two cycles is most sensitive to the expansion efficiency.

Finally, it is observed that the PDE may be best suited for a combined cycle application. Coupling of a PDE, which theoretically can provide static thrust, with a ramjet starting at Mach 2.5 to 3.0, and with a scramjet at Mach 5.0 to 6.0 may be such a possibility.

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4. Heiser, W.H. and Pratt, D.T. (2001) Thermodynamic cycle analysis of pulse detonation engines, J. Propulsion & Power, in preparation.

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